Ringdown and echoes as probes of the nature of compact objects

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Probing the nature of the progenitor and remnant compact objects

Are they really black holes, or exotic compact objects mimicking black holes?

Boson stars, dark matter stars, gravastars, shells, wormholes

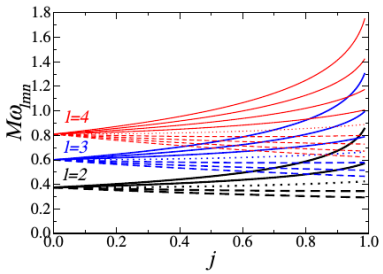
Three "complementary" ways in three different regimes:

- Finite size effects during inspiral.
- No-hair conjecture with quasinormal modes.
- Search for post-merger oscillations or "echoes".

Testing the no-hair conjecture with ringdown quasinormal modes

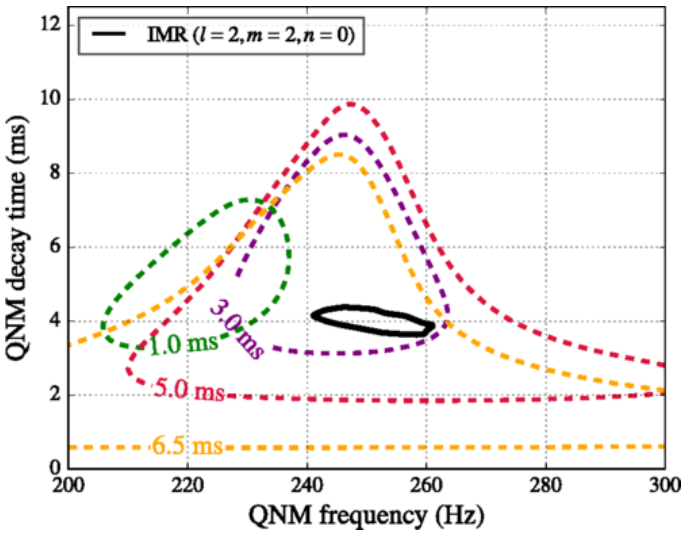
No-hair conjecture: *A stationary black hole in Einstein's general relativity is described only by its mass and spin.*

During ringdown, the quasinormal mode frequencies and damping times will depend only on the mass and spin of the remnant black hole, which can be obtained from linearized Einstein equations on Kerr background.



Berti *et al.* (2006)

$\Rightarrow$ Test for dependences $\omega_{lmn}(M_f, J_f)$, $\tau_{lmn}(M_f, J_f)$.



Abbott *et al.*, PRL **116**, 221101 (2016)

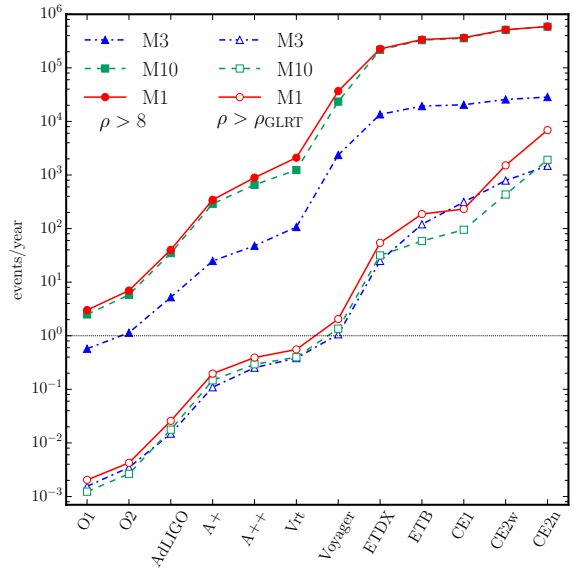
Difficult to measure leading QNM for GW150914.

Testing the no-hair conjecture with ringdown quasinormal modes

Design sensitivity $\sim$ 3 times higher.

Need about 3$\times$ design sensitivity to isolate subleading QNM

Single event!



Berti *et al.* (2016)

Combine information from multiple detections:

- "Coherent mode stacking" — Yang *et al.* (2017)
- "TIGER-like" parameterized deformations — Gossan *et al.* (2011), Meidam *et al.* (2014)

Testing the no-hair conjecture with ringdown quasinormal modes

• Even where one is not able to isolate the individual modes, one can look for systematic departures in the QNM frequencies and damping times from their GR values.

Gossan *et al.* (2011) Meidam *et al.* (2014)

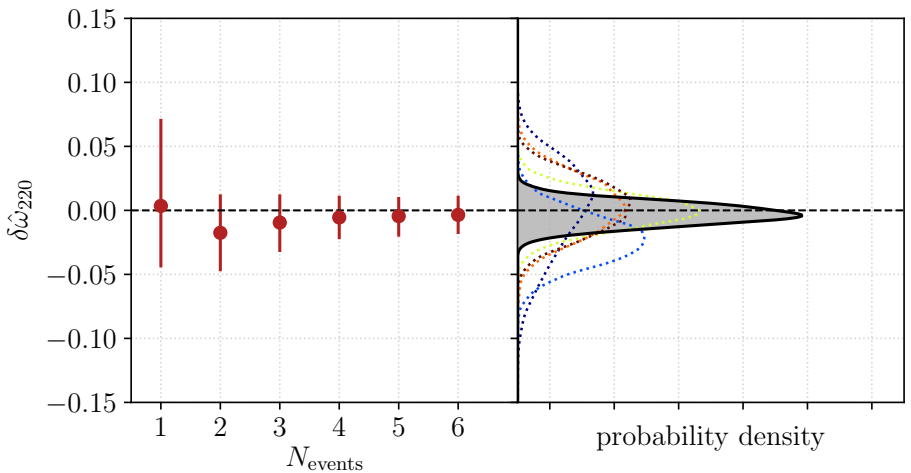
$$\omega_{lmn} = \omega^{GR}_{lmn}(1 + \delta\omega_{lmn}) \,, \quad \tau_{lmn} = \tau^{GR}_{lmn}(1 + \delta\tau_{lmn})$$

• The general expectation was that such tests would become effective only for sources detected by third generation or space-based detectors.

Empirical tests of the black hole no-hair conjecture using gravitational -wave observations

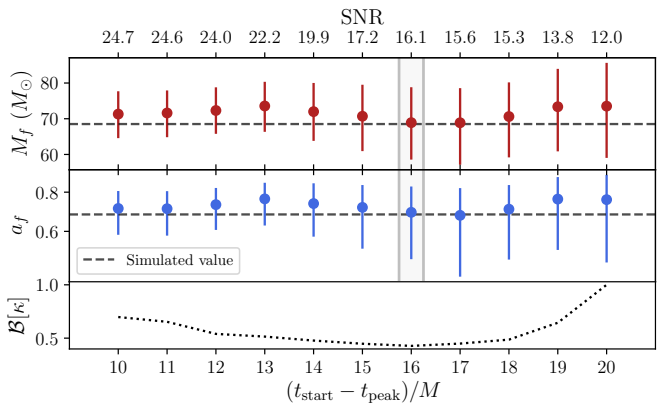
Gregorio Carullo,[1,2,*] Laura van der Schaaf,[2] Lionel London,[3] Peter T. H. Pang,[4] Ka Wa Tsang,[2] Otto A. Hannuksela,[4] Jeroen Meidam,[2] Michalis Agathos,[5] Anuradha Samajdar,[2] Archisman Ghosh,[2] Tjonnie G. F. Li,[4] Walter Del Pozzo,[1,6] and Chris Van Den Broeck[2,7]

- With $\mathcal{O}(5)$ BBH sources similar to GW150914, the systematic departures can be measured with an accuracy of $\sim 1.5\%$ by the Adv LIGO-Virgo at design sensitivity.



- Effective criterion for "start of ringdown" from point of view of parameter estimation.

Carullo *et al.* (2018)



Search for "echoes" after the merger

In a large class of exotic compact objects,

Horizon-scale corrections $\Rightarrow$ secondary bursts of radiation.

Modulated and distorted train of "echoes".

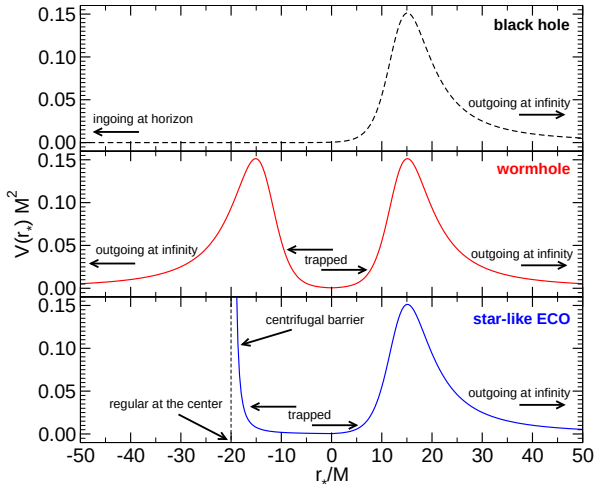
$$\Delta t = nM \log(M/l)$$

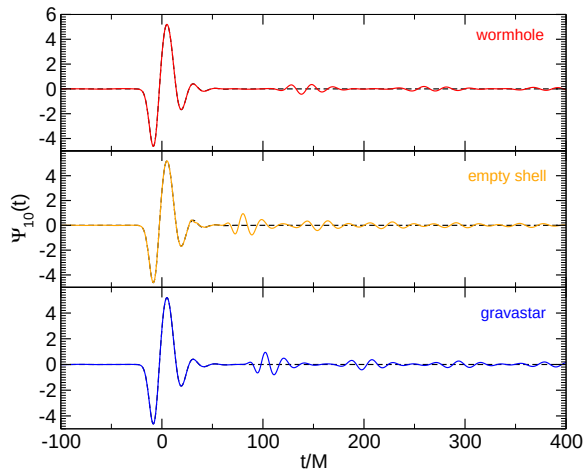
n=8: wormholes

n=4: empty shell

n=6: thin-shell gravastars

Cardoso *et al.* (2016)





Planck-scale corrections can appear relatively soon.

For an event like GW150914, $\Delta t = \mathcal{O}(100\,\mathrm{ms})$, at aLIGO design can hope to see first few echoes.

Can search for "echoes" immediately following the binary-merger detection.

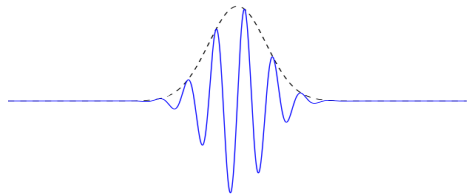
Not sufficiently modelled; Exotic objects not envisaged in literature.

One feature expected to be reasonably robust: constancy of time difference between the subsequent echoes.

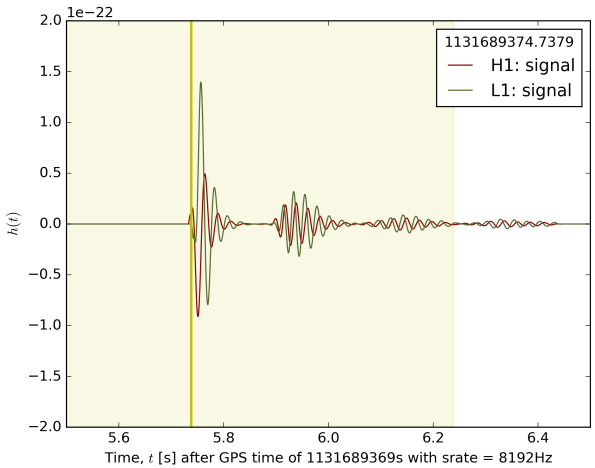
Model-agnostic search and characterization using BayesWave

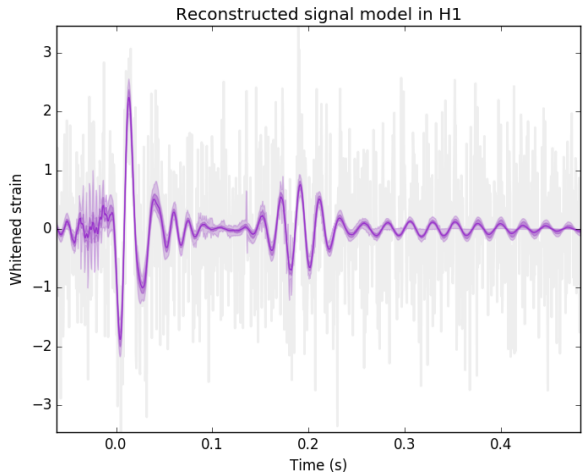
- BayesWave: Morlet-Gabor wavelet reconstruction: Cornish & Littenberg (2015)

$$h(t) = \sum_{j=0}^{N_s} \Psi(t; A_j, f_{0j}, \tau_j, t_{0j}, \phi_{0j})$$



$$\Psi(t; A, f_0, \tau, t_0, \phi_0) = A e^{-(t-t_0)^2/\tau^2} \cos\left(2\pi f_0 (t - t_0) + \phi_0\right)$$





A model-agnostic coherent search for echoes

- Use wavelets that are trains of sine-Gaussians to reconstruct the signal

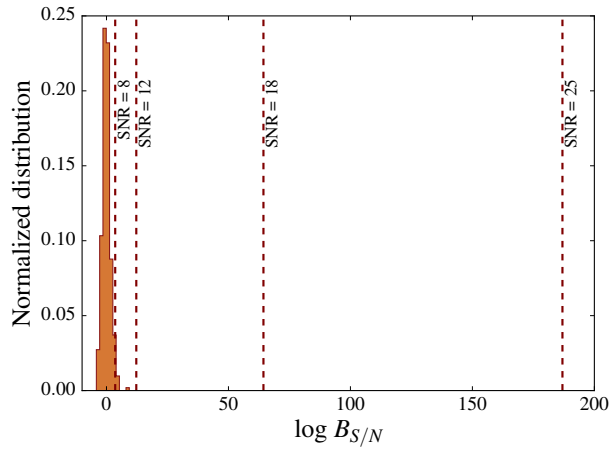
$$\Psi(t; A_n, f_0, \tau, t_n, \phi_n) = \sum_{n=0}^{N_{\text{echoes}}} A e^{-(t-t_n)^2/\tau_n^2} \cos\left(2\pi f_0 (t - t_n) + \phi_n\right)$$

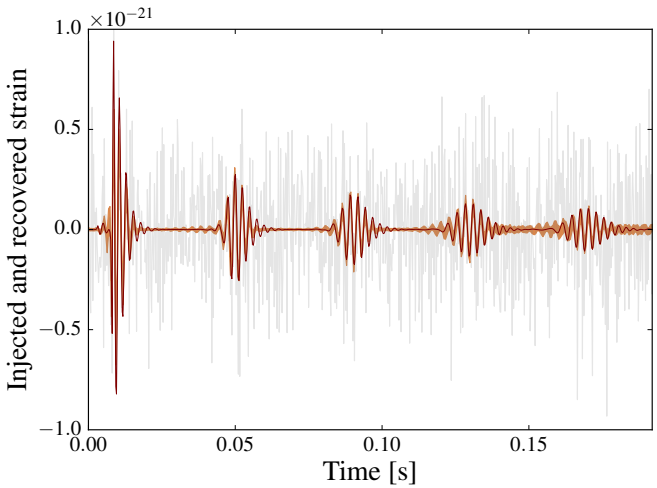
With:

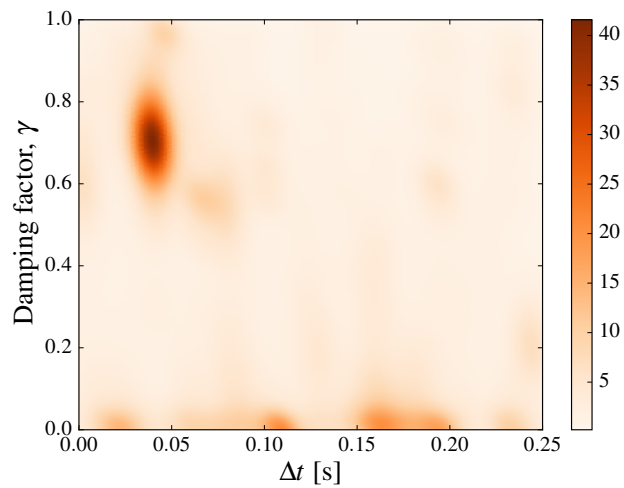
$A_n = \gamma^n A$	damping
$\tau_n = w^n \tau$	widening
$t_n = t_0 + n\Delta t$	time between subsequent echoes
$\phi_n = \phi_0 + 2\pi f_0 n \Delta t + n\Delta\phi$	phase shift subsequent echoes

A morphology-independent data analysis method for detecting and characterizing gravitational wave echoes

Ka Wa Tsang,[1] Michiel Rollier,[1] Archisman Ghosh,[1] Anuradha Samajdar,[1] Michalis Agathos,[2] Katerina Chatziioannou,[3] Vitor Cardoso,[4] Gaurav Khanna,[5] and Chris Van Den Broeck[1,6]



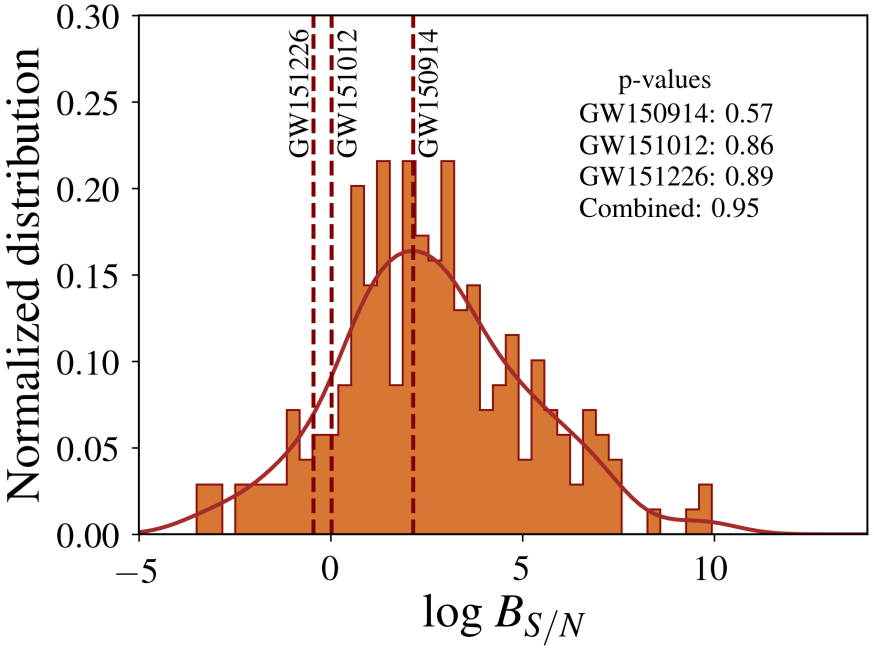


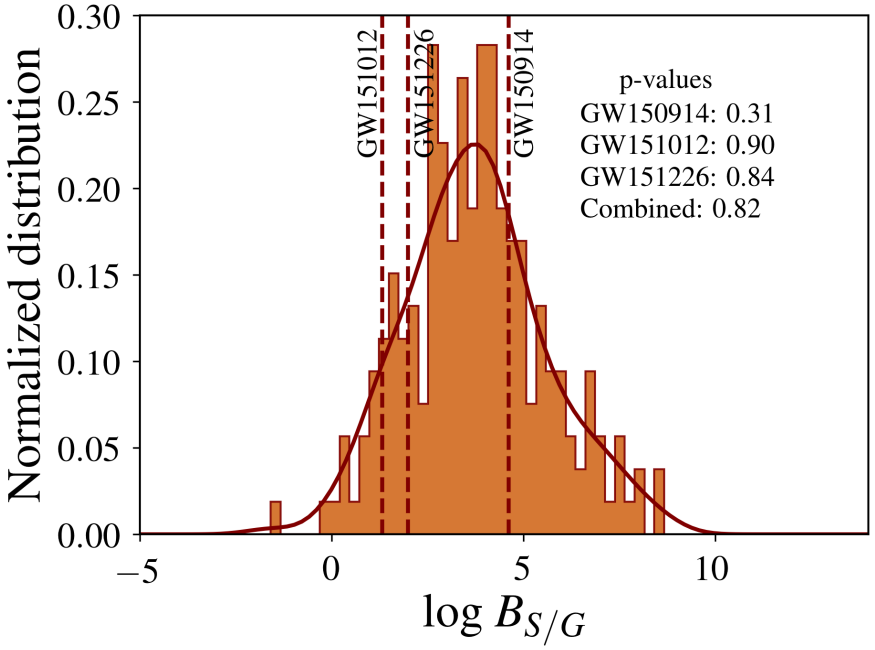


Echoes search at O1 BBH detections - Bayesian evidences

Background calculation:

Analyze $\sim$ 200 8s-segments from GPSTime 1126073529 to 1126075217





All three events are well within the background.

Ευχαριστώ!